Calcium silicate materials in endodontics

Dutta, Arindam; Saunders, William P.

Published in:
Dental Update

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

Arindam Dutta William P Saunders

Calcium Silicate Materials in Endodontics

Abstract: Calcium silicate materials have been recently introduced to dentistry and have found wide applications in endodontics because of their favourable biological properties. This review discusses materials that have become available commercially as well as those that are currently experimental. The compositional aspects of Mineral Trioxide Aggregate (MTA) are discussed with modifications and the development of newer materials. Based upon this information, a definition and classification for calcium silicate materials has been proposed. Calcium silicate materials have properties that make them suitable for use in endodontics. Research with hybrid materials may lead to the development of a cement with more desirable characteristics.

Clinical Relevance: Dentists should be aware of the chemistry of the calcium silicate group of materials that includes Mineral Trioxide Aggregate and several newer materials.

Dent Update 2014; 41: 708–722

The past two decades have witnessed developments in endodontic treatment with strategies that have served to preserve pulpal vitality coupled with the introduction of advanced materials for both surgical and non-surgical root canal treatment. The major emphasis has been on the use of biocompatible and bioactive materials that can lead to the regeneration of both peri-radicular and pulpal tissue, rather than promoting repair. The properties for a material to be used for various endodontic applications (such as a root-end filling, perforation repair, root canal sealer and for pulp capping or pulpotomy) share certain common desirable characteristics. These characteristics are listed in Table 1.

The introduction of Mineral Trioxide Aggregate in 1993 brought about a paradigm shift in the use of dental materials. Subsequent laboratory, animal and clinical studies have established its pre-eminent position for several applications along the dentine-pulp and the pulp space-periradicular tissue continua. Initial animal studies had indicated MTA was associated with minimal inflammation in the periodontal tissues at the site of furcal perforation repair and in the peri-radicular tissues when used as a root-end filling material.[1,2] In both instances, there was also evidence of cementum covering the restoration site. Since these initial studies, there are records of good clinical success when it has been used as a root-end filling material[3,4] (Figures 1 and 2) for root perforation repair,[5] direct pulp capping,[6] apexification[7] and pulpotomy.[8] It has also been used for placement as an apical plug during orthograde endodontic treatment (Figures 3 and 4). The principal constituent of MTA is calcium silicate. Several important properties that develop when the material sets are influenced by the formation of the hydrated calcium silicate phases and its interaction with biological tissue fluid. Innovations in recent years have attempted to overcome the shortcomings of MTA, including relatively long setting time and difficult handling properties, by modifying the composition of this material. Such research has led to the development of a new family of bioactive and biocompatible dental materials for endodontic use that are based on calcium silicate chemistry. This review describes the calcium silicate materials that have been investigated for their application to endodontics with respect to their chemistry and physical properties.

Arindam Dutta, BDS, MDS, MFDS RCPS(Glasg), Specialty Registrar (Restorative Dentistry), Edinburgh Dental Institute, Lauriston Building, Lauriston Place, Edinburgh EH3 9HA and **William P Saunders**, BDS DSc(hc), PhD, FDS RCS(Edin), FDS RCPS(Glasg), FDS RCS(Eng), MRD FHEA FHKCDS, Professor of Endodontology, Consultant in Restorative Dentistry, University of Dundee School of Dentistry, Park Place, Dundee DD1 4HN, UK.

Compositional aspects: Mineral Trioxide Aggregate

The first member of the calcium silicate family of materials to be introduced

for endodontic use was Mineral Trioxide Aggregate. This is composed of Portland cement, with 4:1 addition of bismuth oxide as a radio-opacifier.[9] Portland cement is manufactured by using raw materials that include:

- Lime (CaO);
- Silica (SiO_2);
- Alumina (Al_2O_3); and
- Iron oxide (Fe_2O_3).

These materials are proportioned, blended, fed into a rotary kiln and heated to temperatures of up to 1400–1600˚C. The mixture obtained is the cement clinker which is cooled and pulverized. X-Ray diffraction analyses have revealed that the main constituents of the two different types of MTA (*ProRoot MTA* grey and *ProRoot MTA* white, Dentsply Tulsa Dental Specialties, Johnson City, TN, USA) were tricalcium silicate (C_3S-alite), dicalcium silicate (C_2S-belite), tricalcium aluminate (C_3A-celite), and tetracalcium aluminoferrite (C_4AF-felite) with bismuth oxide.[10] The first formulation of MTA, *ProRoot MTA* was in the form of a grey-coloured powder which had iron as a component in the aluminoferrite phase of the powder.[11] This phase was considered to be important as it allowed a significant setting expansion for the material.[12] However, because the grey colour affected aesthetics, the composition of MTA was altered to reduce the iron content and become more tooth-coloured. This was introduced as white *ProRoot MTA* in March 2002[13] (Figure 5). Its composition has been studied by quantitative X-ray diffraction and this has revealed that the white *ProRoot MTA* is composed of tricalcium silicate (52–53%), dicalcium silicate (22–23%), calcium aluminate (0–4%), bismuth oxide (20–22%) and calcium sulphate dehydrated (approximately 1.5%).[14] Gypsum ($CaSO_4 \cdot 2H_2O$) serves to act as a retarder for the setting reaction and is usually added to the cement clinker at the end of the manufacturing process.[15] Even though these two different types of MTA, namely grey and white *ProRoot MTA*, are primarily composed of tricalcium silicate and dicalcium silicate,[10] the particle size was found to be smaller in the white MTA and X-Ray analysis revealed similar major elements (calcium, silicon and bismuth) but minor elements aluminium, magnesium and particularly iron, were considerably less in the white MTA.[16,17]

- Establish a seal, preferably mediated by a bond between the tooth and the restoration
- Anti-microbial properties
- Biocompatible
- Bioactive with the capability to stimulate and modulate native tissue formation
- Non-absorbable
- Dimensionally stable
- Adequate strength
- Radio-opaque
- Lacks moisture sensitivity
- Easy manipulation characteristics

Table 1. Desirable properties of a material for endodontic application.

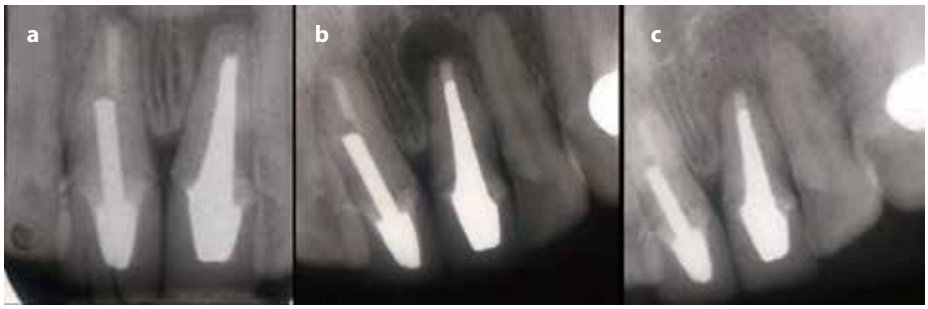


Figure 1. (a) UL1 with long post-retained crown with periradicular lesion. **(b)** Periradicular surgery for UL1 with MTA root-end filling: immediate post-operative radiograph. **(c)** 18 month post-operative review radiograph showing healed lesion.

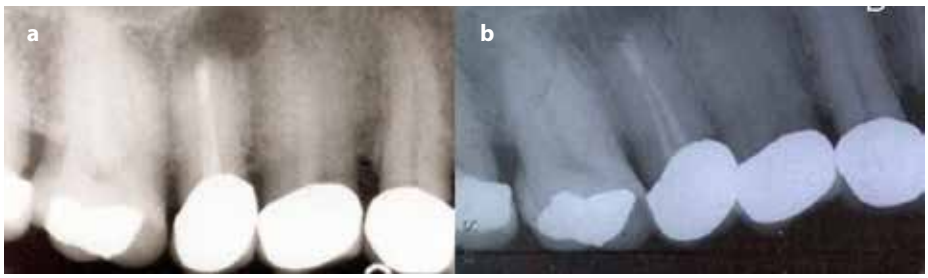


Figure 2. (a) Immediate post-surgical radiograph for UR5 with MTA retrograde restoration. **(b)** 12 month post-operative radiograph showing healed lesion.

As there is similarity in composition between white MTA and white Portland cements (except for bismuth oxide),[18] it was suggested that Portland cement be used as a possible alternative to MTA in dental practice because of the high cost of the latter.[19] This contention was further supported when the properties of a Portland cement with bismuth oxide were compared with white *ProRoot MTA* and found to be very similar in composition, radio-opacity and tissue reaction.[20] However, the amount of gypsum in *ProRoot MTA* was found to be half that found in the Portland cements, thus prolonging the setting time of the latter.[21] Furthermore,

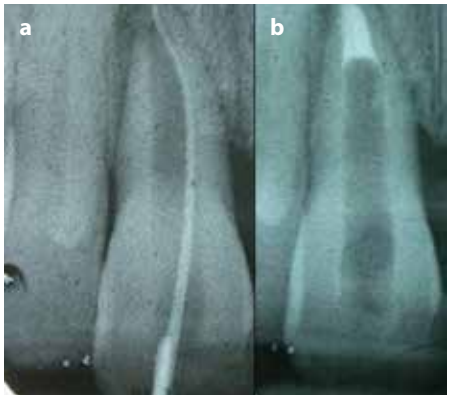


Figure 3. (a) Working length radiograph for UR1 with very wide root canal. **(b)** Orthograde placement of apical MTA plug.

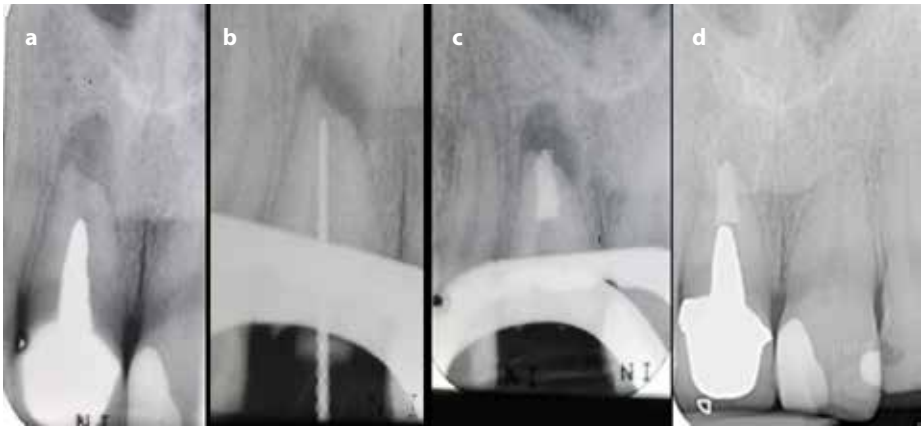


Figure 4. (a) UR1 with long post-retained crown, apical resorption and chronic suppurative periradicular periodontitis. **(b)** Dismantled post-retained crown and working length radiograph in orthograde treatment approach. **(c)** Immediate post-operative radiograph following placement of tooth-coloured *ProRoot MTA* apical plug. **(d)** 15 month post-operative radiograph showing continued healing.

Figure 5. (a) *ProRoot MTA*. **(b)** Individual, single use *ProRoot MTA* sachet with distilled water.

the *ProRoot MTA* consisted of fewer toxic heavy metals (copper, manganese and strontium), fewer chromophores (Fe^{3+}) and fewer aluminium species but contained 20% bismuth.[21] Additionally, the Portland cements were composed of particles with a wide size range, while the *ProRoot MTA* was found to have smaller particles of uniform size that could affect the setting reaction for the cement. Thus, there is a significant difference between MTA and Portland cements and it is not recommended to substitute MTA with Portland cement for clinical use.

Setting reaction

Portland cements and the calcium silicate family of materials can also be termed hydraulic cements. Such cements are composed of several phases. When the cement is mixed with water, a chemical reaction occurs between these phases and water and is known as hydration. Grey MTA comprises compositional phases, namely alite (tricalcium silicate, C_3S), belite (dicalcium silicate, C_2S), celite (tricalcium aluminate, C_3A) and felite (tetracalcium aluminoferrite, C_4AF), that hydrate and harden at different rates.[22] Celite hardens the quickest and results in a flash set. Therefore, gypsum is added to the cement to retard this reaction. Felite also hardens rapidly but contributes little to strength. Alite hydrates rapidly and is responsible for initial setting and strength. Belite has a slow hydration reaction and helps develop strength properties beyond the first week. The hydration of white *ProRoot MTA* has been reported to consist of two separate reactions.[14,23] The initial reaction occurs between tricalcium aluminate and water which, in the presence of gypsum (found in small quantities in MTA), results in the production of ettringite (hydrous calcium aluminium sulphate, chemically $Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$). This later forms monosulphate upon the depletion of gypsum. When calcium silicate cements make contact with water, calcium ions are rapidly leached from the solid to form calcium hydroxide solution. It has been found that the hydrated, calcium-depleted surface of grains consists of low molecular mass silicic acids and that these interact with dissolved hydroxylated calcium species (principally $Ca(OH)_2$, also known as Portlandite) to produce a semi-permeable membrane of calcium silicate hydrate (C-S-H) at the hydrated grain surface.[24] This has been termed the Pozzolanic reaction and can be characterized as:

$$Ca(OH)_2 + H_4SiO_4 \rightarrow Ca^{2+} + H_2SiO_4^{2-} + 2\,H_2O \rightarrow CaH_2SiO_4\cdot 2\,H_2O$$

This C-S-H gel phase formed over the grain surface has been termed the *inner product*.[23] Osmotic pressure within the C-S-H gel phase may cause it to rupture and promote the growth of excrescences from the grain as the contents are extruded into the surrounding calcium hydroxide solution, which leads to the formation of the *outer product*.[23,24] The overall hydration reaction of alite that leads to the formation of the C-S-H phase is represented as follows:

$$2\,Ca_3SiO_5 + 7\,H_2O \rightarrow 3\,CaO\cdot 2\,SiO_2\cdot 4\,H_2O + 3\,Ca(OH)_2 + 173.6\ kJ$$

Set hydrated cement is composed of numerous residual unhydrated cement grains, which have a dense rim of hydration product, made up of pure calcium silicate hydrate.[23] Some ettringite and monosulphate may be present. Unreacted bismuth oxide particles and calcium hydroxide have also been detected. These have a tendency to leach out from the cement.[11] The leaching of calcium ions from the cement is critical for the development of biological properties of the calcium silicate material.[25] The C-S-H phase has also been shown to take up bismuth, which replaces the silica in the gel.

Manipulation

ProRoot MTA is not a perfect dental material. A granular consistency results in relatively poor handling characteristics making it difficult to deliver to the clinical site and challenging to condense.[26] To enhance manipulation, special carrier and syringeable type systems, such as the *Retro Amalgam Carrier* (Moyco Union Broach, York, PA, USA), *Messing Root Canal Gun* (R Chige Inc, Boca Raton, FL, USA) (Figure 6), *Centrix* syringe (Centrix, Inc, Shledon, CT, USA), *Dovgan* (Quality Aspirators, Duncanville, TX, USA), *MTA Carrier* (G Hartzell & Son, Concord, CA, USA), disposable *MTA Carrier* (Vista Dental Products, Racine,

WI, USA) and *Micro Apical Placement* system (Dentsply Maillefer, Ballaigues, Switzerland) were introduced to aid MTA placement clinically (Figure 7). In another approach, a *Pellet-forming Block* (G Hartzell & Son, Concord, CA, USA) was introduced; in this system mixed MTA was placed into the designated areas (grooves of various sizes) on the so-called Lee block, which helped shape the unset material into a pellet which could then be retrieved with a flat plastic instrument[27] (Figure 8). MTA is placed into several grooves after mixing so that increments can be quickly retrieved and placed without causing any dehydration of the cement.

Modifications to composition

Though the expensive devices mentioned above allow simpler placement, the inherent flaw in the chemistry or physical properties of MTA that affect its workability remained unchanged. This was compounded by the susceptibility of MTA to wash out in the presence of excess moisture.[26] Additionally, even though MTA allows a good working time, the material has a prolonged setting time, making its utilization in restorative dental procedures cumbersome, sometimes necessitating two visits for the completion of treatment. To overcome these basic difficulties and further improve its properties, the composition of MTA has been modified. This section discusses the modifications to MTA chemistry, the development of newer calcium silicate materials and, finally, the creation of a new generation of hybrid materials that have calcium silicate chemistry as a part of their overall structure.

Modifications to decrease setting time and improve handling properties

The setting time of MTA, at 2 hours and 45 minutes, is longer than

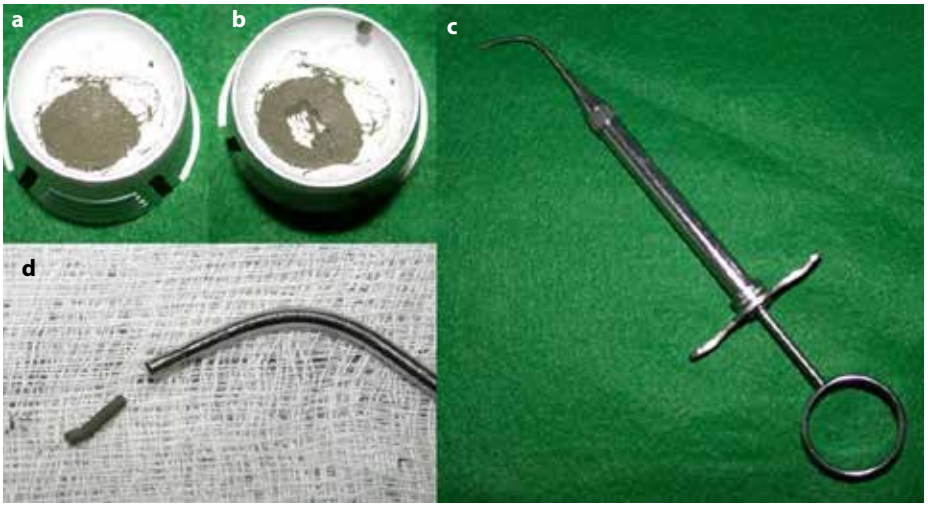


Figure 6. (a) Grey *ProRoot MTA* mixed with distilled water. **(b)** Excess moisture soaked-up with gauze leaving a moist mixture. **(c)** Messing Root Canal Gun, R Chige Inc, Boca Raton, FL, USA. **(d)** Cylindrical shape of MTA increment delivered by the carrier.

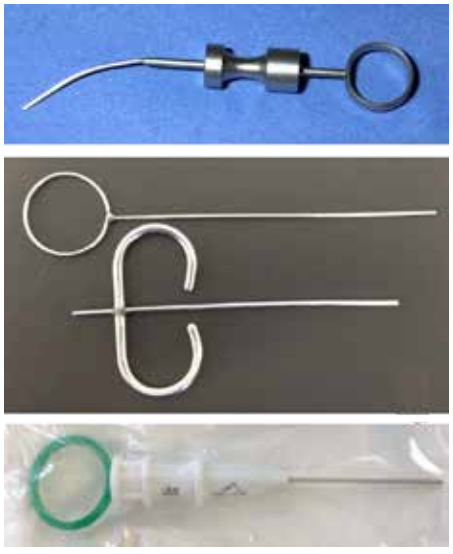
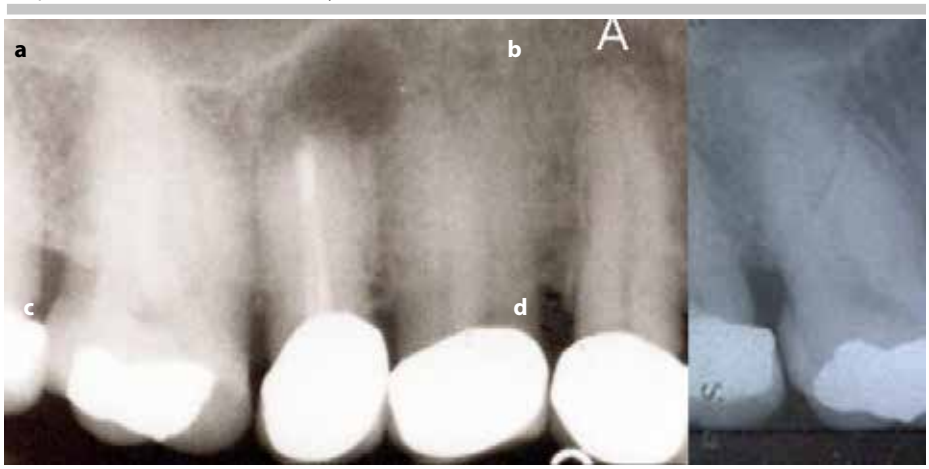


Figure 7. (a) *Dovgan* carrier, Quality Aspirators, Duncanville, TX, USA. **(b)** *MTA Carrier*, G Hartzell & Son, Concord, CA, USA. **(c)** Disposable *MTA Carrier*, Vista Dental Products, Racine, WI, USA.



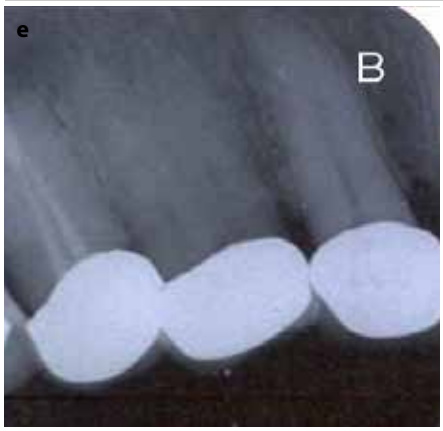


Figure 8. (a) Lee pellet-forming block. **(b)** Mixed White *ProRoot MTA*. **(c)** MTA placed in multiple grooves on Lee Block. **(d)** Cylindrical pellet retrieved with Hollenback instrument for root-end filling. **(e)** Pluggers for root-end cavities.

acceptable for most restorative clinical procedures.[28] In order to decrease setting time, several strategies have been used for accelerating the hydration reaction of the cement. One of the earliest reports used 10% and 15% $CaCl_2$ added to an accelerated Portland cement (Rugby cement, Rugby, UK) that helped decrease setting time and was found to be non-toxic.[29]

MTA Angelus (Angelus Soluções Odontológicas, Londrina, Brazil) was introduced in 2001 and is composed of 80% Portland cement and 20% bismuth oxide.[30] Calcium sulphate, a retardant for hydration, was eliminated from its composition to help decrease the setting time. Initially, *MTA Angelus* was grey in colour and was later changed to a white coloured material which was named *MTA Branco*.[31]

The use of various additives and mixing liquids has been another strategy to help improve the setting time of MTA. Several compounds have been tested, some of which also help improve the handling characteristics of the cement. Calcium formate reduced the setting time by 90%, KY Jelly and 5% $CaCl_2$ decreased this by 50–64%, 3% $CaCl_2$ did not alter setting times, saline and 2% lidocaine with 1:100,000 epinephrine delayed the setting time by 80% and 140%, respectively, and MTA did not set with 2% chlorhexidine gluconate gel.[26,32,33] Even though 3% NaOCl gel decreased setting times, the reported reduction varied from 30–60%.[26,30] *ProRoot MTA* (white) mixed with 15% sodium phosphate dibasic (pH 9.5) set at 26 min and with 15% monobasic sodium phosphate (pH 4.4), within 33 min, as compared with distilled water at 150 min.[34] 0.1% citric acid has been found to be similar to 10% $CaCl_2$ as an accelerant but reduced the compressive strength of *ProRoot MTA* from 39 MPa to 27.23 MPa.[35]

A Nano white MTA (NWMTA) has been described with small amounts of Sr to improve bioacitivity and a reduced particle size that resulted in an increased surface area (7.8 m^2g^{-1}) as compared with white *ProRoot MTA* (WMTA) (1. 8 m^2g^{-1}).[36] This helped reduce the intial setting time from 43 min (WMTA) to 6 min (NWMTA) and also increased the microhardness of NWMTA.

The use of an admix of 1–3% methyl cellulose (improved cohesiveness) and 2% calcium chloride (accelerant) with grey *ProRoot MTA* resulted in a mix that handled in a similar way to a reinforced zinc oxide eugenol cement and set three times faster (57±3 min) than an unmodified MTA.[37] 23.1% calcium lactate gluconate (CLG), as a dual functional additive reduced setting times to 12 min, with better handling properties than *ProRoot MTA* mixed with water or $CaCl_2$ · CLG. It also helped rapid initial set by supplying Ca^{2+} and reducing the free water in the cement, with subsequent precipitation of amorphous CLG that behaved as a plasticizer. Even though $CaCl_2$ acts as an effective accelerant, because of its crystalline nature, it tended to precipitate as sand-like particles and offered less enhancement of cement cohesiveness.[38] However, it reduced compressive strength of the material significantly.[35]

Modifications for radio-opacifiers

The original radio-opacifier used in MTA was bismuth oxide. However, authors have reported that increasing the concentrations of bismuth oxide affected material properties adversely by increasing porosity (from 15–31%). This may lead to greater solubility and degradation of the material.[39] Even though there are studies that have shown a lack of tissue response to Portland cements containing bismuth oxide,[20,40] it has also been shown to induce cytotoxicity in dental pulp cells.[41] The ISO specification for dental root canal sealing materials states that radio-opacity should be greater than a 3 mm thickness of aluminium (Al).[42] Even though the radio-opacity of Portland cement with bismuth oxide was found to be the best (5.88 mm Al), both zirconium oxide (3.87 mm Al) and iodoform (3.5 mm Al) also surpassed the ISO standard. Barium sulphate in Portland cement displayed values below those recommended by the standard (2.35 mm Al). Another white Portland cement has been modified by the addition of ZrO_2 or calcium tungstate but has significantly increased the final settings times (more than 300 min).[43]

Modification for application as root canal sealers

Several sealers based on the calcium silicate chemistry have become available recently and include:

- Endo CPM™ sealer (Egeo SRL, Buenos Aires, Argentina);
- *MTA Sealer*;
- *MTA Fillapex* (Angelus Indústria de Produtos Odontológicos Londrina, Brazil);
- *iRoot SP* (also known as *Endosequence BC* sealer) (Innovative BioCeramix Inc, Vancouver, Canada);
- *Tech Biosealer Endo* (Isasan SRL, Rovello Porro, CO, Italy and discussed in a subsequent section); and
- Experimental fluoride-doped calcium silicate sealers.

One of the first calcium silicate sealers to be reported in the literature was the Endo CPM™ sealer (Egeo SRL).[44] This sealer consists of 50% MTA (SiO_2, K_2O, Al_2O_3, SO_3, CaO and Bi_2O_3); 7% SiO_2, 10% $CaCO_3$, 10% Bi_2O_3, 10% $BaSO_4$, 1% propylene glycol alginate, 1% propylene glycol, 1% sodium citrate and 10% $CaCl_2$ (as per manufacturer).[45]

iRoot SP (Innovative BioCeramix Inc) was first reported as a root canal sealer in 2009. The material has also been retailed as *SmartPaste Bio* (SmartSeal DRFP Ltd, Stamford, UK). According to the manufacturer's description, the sealer is a convenient, premixed, ready-to-use injectible white hydraulic cement paste developed for permanent root canal filling and sealing applications. The sealer is also supplied with root canal obturation points termed *ProPoints*. *ProPoint* (also made available as C point, LLC, Shrewsbury, MA, USA), has a radio-opaque polyamide core coated with a hydrophilic polymer coating. The sealer is an insoluble, radio-opaque, aluminium-free material based on a calcium silicate composition, which requires the presence of water to set and harden.[46] This material has also been licensed as *EndoSequence BC Sealer* (Brassler, Savannah, GA, USA) and *Hyseal-bio* (LLC, Shrewsbury, MA, USA). Brassler has also made available a Root Repair Material in the form of a mouldable putty and a preloaded syringe with delivery tips. The manufacturer has stated that it is composed of calcium silicates, zirconium oxide, tantalum oxide, calcium phosphate monobasic and filler agents. It has a working time of 30+ min and final set is achieved within approximately 4 hours.

The Root Repair Material is bioactive.[47] The material is nanofilled, allowing good adaptation to the root canal and flow into open dentinal tubules.

Other calcium silicate materials

New Endodontic Cement (NEC) consists of different calcium compounds (calcium oxide, calcium phosphate, calcium carbonate, calcium silicate, calcium sulphate, calcium hydroxide and calcium chloride).[48] This was later termed the Calcium Enriched Mixture (USPTO number: 7,942,961). The setting time was significantly shorter than *ProRoot MTA* (50 min as against 70 min). It has been shown to have good handling, provide an effective seal[49] and bioactivity.[50] Electron probe microanalysis revealed that there were compositional differences in NEC and *ProRoot MTA*.

In 2009, the first study on Bioaggregate (DiaRoot® Bioaggregate, Innovative BioCeramix Inc, Vancouver, BC, Canada) was published regarding its antibacterial effects.[51] It has been described as a bioceramic material intended for perforation repair and root-end filling. It is a laboratory-synthesized, water-based cement which is claimed to be produced under controlled conditions, resulting in a pure and fine white hydraulic cement-like powder composed of contamination-free biocompatible ceramic nanoparticles.[52] Its composition has been described as being aluminium free.[51] The components of DiaRoot® Bioaggregate are tricalcium silicate (41%), dicalcium silicate (24%), tantalum pentoxide (25%), calcium phosphate monobasic (6%) and amorphous silicon oxide (4%).[52] The liquid supplied with the material consists of 100% deionized water. The hydrated cement has grains surrounded by a matrix of calcium silicate hydrate and calcium hydroxide with a phosphate-containing phase.[53] Since the studies by Zhang *et al* and Park *et al*,[51,54] several biological studies for Bioaggregate have been performed. The material has the ability to form surface apatite crystals that help contribute to bioactivity.[47] It has a long setting time (1260 min), low washout and mechanical properties (compressive strength 16.34 MPa, Vickers hardness 10.7) and high fluid uptake and water sorption.[55]

Biodentine™ (Septodont, Saint Maur des Fossés, France) is a calcium silicate based material introduced in 2010 with several clinical applications. The material is available as a unit dose in a disposable capsule. The liquid is provided separately and needs to be added to the capsule which can then be closed and vibrated in a mechanical mixer to obtain a homogeneous mix (Figure 9). The powder is composed of tri-calcium silicate (main core material), di-calcium silicate (second core material), calcium carbonate and oxide (fillers), iron oxide (shade) and zirconium oxide as the radio-opacifier.[56] The liquid contains calcium chloride as the accelerator and a hydrosoluble polymer as the water reducing agent, also known as superplasticizers. The setting time claimed by the manufacturer is within 9–12 minutes. Compressive strength values were 241 MPa as against 7.5MPa for *ProRoot MTA* at 24 hours. Clinical applications include:

- Use as a dentine substitute under composite;
- Use for direct pulp capping;
- Pulpotomy in primary molars;
- Apexification;
- As a root-end filling material; and
- Perforation repair.

While setting, the material has hydrating cement grains surrounded by a matrix of calcium silicate hydrate and calcium hydroxide along with the presence of calcium carbonate.[53] The uptake of calcium and silicon by dentine from Biodentine™ is more than white *ProRoot MTA* in the presence of phosphate buffered saline.[57] An interfacial interaction via a dynamic mineral interaction zone has been reported between Biodentine™ and dentine.[58] The material has a high washout, low fluid uptake and sorption, low setting time (45 min) and superior mechanical properties (compressive strength 67.18 MPa and Vickers hardness 48.4).[55]

Tech Biosealer (Isasan SRL, Rovello Porro, CO, Italy) is a material with different powders designed for varied applications. It is composed of Portland cement white CEM 1, calcium sulphate hemihydrate, calcium chloride, bismuth oxide, montmorillonite and sodium fluoride. Montmorillonite is a phyllosilicate mineral characterized by high and irreversible swelling capacity owing to water adsorption. Chemically, it is hydrated sodium calcium aluminium magnesium silicate hydroxide $(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$. The cement has a unique mixing liquid composed of Dulbecco's phosphate buffered saline.[59] There are four formulations for the material according to their application: for use as a sealer (*Tech Biosealer* endo), apexification (*Tech Biosealer* apex), root-end filling (*Tech Biosealer* root end) and pulp capping (*Tech Biosealer* capping).[60] The hydration of the cement, kinetics of the reaction and nanostructure formation have been studied using time-domain nuclear magnetic resonance and this revealed a faster set for the material than *ProRoot* white MTA.[61] The material is bioactive with the formation of apatite on its surface, biocompatible and with good apical seal.[62–64]

MTA Plus (manufactured by Prevest-Denpro, Jammu City, India for Avalon Biomed, Bradenton, FL, USA) is a powder-liquid system with the option of mixing the powder (tricalcium and dicalcium silicate, bismuth oxide, calcium sulphate and silica) with either water

Figure 9. (a) *Biodentine*. **(b)** Liquid and disposable capsule containing *Biodentine*.

Generation	Calcium Silicate Materials
Generation I	■ Grey MTA ■ White MTA
Generation II +	■ Modifications to MTA – To decrease setting time: with calcium chloride, sodium hypochlorite, *KY Jelly*, calcium nitrite, calcium nitrate dicalcium formate, sodium phosphate dibasic – To improve handling: methyl cellulose – Dual functional (faster set and better handling): calcium lactate gluconate – Alteration in bismuth oxide concentration – Replacement of bismuth oxide with alternative radio-opacifier: zirconium oxide, iodoform, silver-tin alloy, gold, titanium ■ *MTA Angelus, MTA Branco* and *MTA Bio*
Generation III	■ Modification of Portland Cement: several experimental cements ■ Modification for use as sealer: *Endo CPM, ProRoot Endo* (with water soluble polymer), MTAs, *iRootSP* (also retailed as *Endosequence BC* and *SmartPaste Bio*), *MTA Obtura, Tech Biosealer Endo*, experimental fluoride doped cement ■ Calcium silicate materials: – Synthesized as a partial-stabilized cement – Synthesized via sol-gel method – Aluminium-free cement – New Endodontic Cement/Calcium Enriched Mixture – Bioaggregate – *Biodentine* – *Tech Biosealer* (with accelerator and phyllosilicate plasticizer) – *Aureoseal* – *Ortho MTA* – *MTA Plus* – Experimental cements: – Calcium sulpho-aluminate cement with or without granite – Calcium fluoro-aluminate cement with or without granite – Additives of Mg, Zn, Fe – Calcium aluminate-calcium silicate composite cement – *Generex A*, *Generex B* – *Ceramicrete-D* – *Capasio*
Generation IV	■ Hybrid cements: – Calcium phosphate/Calcium silicate/Bismutite cement – NRC (Incorporating HEMA) – MTA with 4-META/MMA-TBB – Light-cured cements including *TheraCal LC*

Table 2. Classification of calcium silicate materials.

or an anti-washout gel (AWG), the latter accelerating the set of the material, as per manufacturer's claim, to one hour.[65,66] The anti-washout property helps prevent disintegration of the cement when exposed to fluids, which may happen when the surgical site is rinsed with an irrigant. The AWG is a water soluble polymer composed of approximately 97.8% water mass and traces of SiO_2, K_2O, Cl and CaO.[66] The AWG used with *MTA Plus* reduces the material washout and is similar to amalgam and IRM as compared with *MTA Plus* with water or *MTA Angelus*.[67] The hydration reaction of the powder mixed with the AWG is different from water, with larger reaction rims around the unhydrated cement particles seen with the former.[66] With AWG, calcium ion released was significantly less than with water at 14, 21 and 28 days, the setting time was reduced by 65 minutes to 100 minutes and the compressive strength was significantly higher, both when dry and immersed in HBSS.[66] A zone of collagen degradation has been identified from the surface of dentine exposed to *MTA Plus* that was associated with minimal amounts (picograms) of dentinal loss.[68]

Hybrid calcium silicate cements

The adaptation of calcium silicate material chemistry by incorporating it with a completely different material has led to the development of a hybrid category of materials. A self-setting, pulp-capping cement composed of calcium phosphate/calcium silicate and bismutite ($Bi_2O_2CO_3$), named calcium phosphate/calcium silicate/bismutite cement (CPCSBi) was designed to maximize the advantages from each constituent.[69] The dissoluble dentine matrix components extracted from CPCSBi exposed to dentine powder demonstrated increased expression of dentine sialophosphoprotein (DSPP) and sotecalcin in human pulp cells which indicated its suitability as a pulp-capping agent.

A calcium silicate cement, mainly based on dicalcium silicate and tricalcium silicate, was prepared using 5% calcium chloride additive and further mixed with alpha-tricalcium phosphate to help apatite formation.[70] Dulbeco's phosphate buffered saline was used as the mixing liquid. The cement displayed high bioactivity and human marrow stromal cell proliferation.

A novel root-end filling material, termed NRC, has been developed from bioactive powders and a hydroxylethylmethacrylate (HEMA)-based resin monomer.[71] The powder consists of 33.4% calcium oxide, 33.3% calcium silicate and 33.3% triphenylbismuth carbonate. The liquid is a mixture of hydroxyethylmethacrylate (10 ml), benzoyl peroxide (0.03 g), N-N-dimethyl-para-toluidine (0.02 ml) and sodium para-toluenesulphinate (0.01 g). NRC sets in 12.5 minutes, with compressive strength and pH similar to white MTA. It was not found to be cytotoxic.

The first light-cured Mineral Trioxide Aggregate material was introduced in 2008.[72] Light-cured MTA presented a moderate chronic inflammatory that was more intense than with *Angelus MTA* and without dystrophic calcifications. The light-cured MTA consisted of AeroSil (fumed silica) 8%, biocompatible hydrophilic resin 42.5% (which in turn was composed of BisGMA 20%, proprietary biocompatible resin [FDA] 77.25%, modifying agent 2.4%, initiating agent 0.32%, stabilizer for the initiating agent 0.032%), active ingredients in MTA 44.5% and barium sulphate 5%.[72] The light-cured MTA displayed the least solubility values and calcium release.

Another light-cured MTA product has been reported recently.[73] The powder is composed of di- and tri-calcium silicates, tricalcium aluminate, barium sulphate, calcium sulphate and calcium chloride. The liquid phase contained 2-hydroxyethyl methacrylate, triethyleneglycol dimethacrylate (TEGDMA), camphoroquinone and ethyl-4-(dimethylamino) benzoate. The cement sets in 2 minutes with a high calcium ion release (150–200 ppm) and alkalinity (pH 10–12). Formation of bone-like apatite spherulites was observed after 1 day and the cement had good marginal adaptation. The cement also allowed Saos-2 cell viability and growth and no toxicity was observed. The presence of HEMA-TEGDMA hydrophilic resins helped create a polymeric network that was able to stabilize the outer surface of the cement and also the hydrophilic matrix that was capable of water sorption. Rapid nucleation for apatite formation occurred via the hydration of the silicates and the chelation of calcium to oxygen-containing groups of the resin.

TheraCal LC (Bisco Inc, Schaumburg, IL, USA) is a light-cured, resin-modified, calcium silicate filled liner used for direct and indirect pulp capping as well as under different restorative materials. The material is composed of Portland cement Type III (20–60%), polyethylene glycol dimethacrylate (10–50%), bisphenol A diglycidyl methacrylate (5–20%) and barium zirconate (1–10%).[74] The cytotoxicity of the material has been tested.[75] *TheraCal* demonstrated a reduction in cell metabolism ranging from 31.5% to 45.9% which was lower than for *Vitrebond* (73–77%) and *Ultrabend Plus* (64–71%). It has higher calcium-releasing ability and lower solubility than *ProRoot MTA*, does not meet the ISO 6876 guideline regarding radio-opacity, and may be cured to a depth of 1.7 mm to prevent dissolution.[76]

A study has also examined the possibility of using 4-methacryloxyethyl trimellitate anhydride/methylmethacrylate-tri-n-butyl borane (4-META/MMA-TBB) with Mineral Trioxide Aggregate to overcome the shortcomings of the latter.[77] The authors mixed MTA powder with the liquid of 4-META/MMA-TBB resin and found the cement to set faster (11 vs 318 minutes for MTA) with less leakage. The pH for MTA was higher during the entire period of the study, though the differences between the two cements were significant only for the first 48 hours. Both cements did not reveal any cytotoxicity.

Calcium-aluminosilicate or fluoride-containing calcium-aluminosilicate Portland-derived mineral powders have been mixed with methacrylate HEMA/TEGDMA/polyacrylic acid-based resin to prepare experimental composites. These are ion-leachable composites that possessed the ability to remineralize human apatite-depleted dentine surfaces.[78]

Light-cured and chemically-cured composites have been developed using *MTA Plus* or *MTA Plus* mixed with water.[79] The resin itself did not chemically react with the cement powder, which remained unhydrated within the composite. More apatite formation was seen on the surface for the *MTA Plus* mixed with water, as was a higher alkalinity (12.7) and calcium ion concentration. The chemically cured composite had the lowest values.

Summary of modification to composition

Several modifications have been made to the original MTA formulation, some of which have resulted in the development of new products with a decreased setting time and improved handling characteristics. Several experimental variants of Portland cement with additives have also been investigated. Calcium silicate materials have also been mixed with other materials to enhance their properties. Based on the variety of materials available and under investigation, *calcium silicate cements* (for use in dentistry) may be *defined as those that are composed (at least in part), of either di-/tri-/tetra- calcium silicate phases with a hydration process that is the sole or contributory mechanism for the setting reaction which results in the formation of leachate and crystalline phases that promote bioactivity*. Based on their chemistry, a classification for calcium silicate materials is proposed (Table 2).

Conclusions

The introduction and development of calcium silicate-based materials has provided many opportunities for their use in endodontics. The materials have enhanced the successful outcomes of several endodontic procedures. This review has demonstrated the continuing development of materials with suitable

chemical and handling properties that allows their application for a variety of clinical needs, including root-end fillings, sealers and pulp-capping agents.

References

1. Ford TR, Torabinejad M, McKendry DJ, Hong CU, Kariyawasam SP. Use of mineral trioxide aggregate for repair of furcal perforations. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 1995; **79**: 756–763.
2. Torabinejad M, Hong CU, Lee SJ, Monsef M, Pitt Ford TR. Investigation of mineral trioxide aggregate for root-end filling in dogs. *J Endod* 1995; **21**: 603–608.
3. Saunders WP. A prospective clinical study of periradicular surgery using mineral trioxide aggregate as a root-end filling. *J Endod* 2008; **34**: 660–665.
4. Christiansen R, Kirkevang L-L, Hørsted-Bindslev P, Wenzel A. Randomized clinical trial of root-end resection followed by root-end filling with mineral trioxide aggregate or smoothing of the orthograde gutta-percha root filling – 1-year follow-up. *Int Endod J* 2009; **42**: 105–114.
5. Mente J, Hage N, Pfefferle T, Koch MJ, Geletneky B, Dreyhaupt J *et al*. Treatment outcome of mineral trioxide aggregate: repair of root perforations. *J Endod* 2010; **36**: 208–213.
6. Mente J, Geletneky B, Ohle M, Koch MJ, Friedrich Ding PG, Wolff D *et al.* Mineral trioxide aggregate or calcium hydroxide direct pulp capping: an analysis of the clinical treatment outcome. *J Endod* 2010; **36**: 806–813.
7. Chala S, Abouqal R, Rida S. Apexification of immature teeth with calcium hydroxide or mineral trioxide aggregate: systematic review and meta-analysis. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2011; **112**: e36–e42.
8. Erdem AP, Guven Y, Balli B, Ilhan B, Sepet E, Ulukapi I *et al*. Success rates of mineral trioxide aggregate, ferric sulfate, and formocresol pulpotomies: a 24-month study. *Pediatr Dent* 2011; **33**: 165–170.
9. Torabinejad M, White DJ. United States Patent: 5415547 – Tooth filling material and method of use [Internet]. 1995 [cited 2013 Mar 4]. Available from: **http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO1&Sect2=HITOFF&d=PALL&p=1&u=%2Fnetahtml%2FPTO%2Fsrchnum.htm&r=1&f=G&l=50&s1=5415547PN.&OS=PN/5415547&RS=PN/5415547**
10. Camilleri J, Montesin FE, Brady K, Sweeney R, Curtis RV, Ford TRP. The constitution of mineral trioxide aggregate. *Dent Mater* 2005; **21**: 297–303.
11. Camilleri J. The chemical composition of mineral trioxide aggregate. *J Conserv Dent* 2008; **11**: 141–143.
12. Storm B, Eichmiller FC, Tordik PA, Goodell GG. Setting expansion of gray and white mineral trioxide aggregate and Portland cement. *J Endod* 2008; **34**: 80–82.
13. Bozeman TB, Lemon RR, Eleazer PD. Elemental analysis of crystal precipitate from gray and white MTA. *J Endod* 2006; **32**: 425–428.
14. Camilleri J. Characterization of hydration products of mineral trioxide aggregate. *Int Endod J* 2008; **41**: 408–417.
15. Camilleri J, Montesin FE, Di Silvio L, Pitt Ford TR. The chemical constitution and biocompatibility of accelerated Portland cement for endodontic use. *Int Endod J* 2005; **38**: 834–842.
16. Asgary S, Parirokh M, Eghbal MJ, Stowe S, Brink F. A qualitative X-ray analysis of white and grey mineral trioxide aggregate using compositional imaging. *J Mater Sci Mater Med* 2006; **17**: 187–191.
17. Asgary S, Eghbal MJ, Parirokh M, Ghoddusi J, Kheirieh S, Brink F. Comparison of mineral trioxide aggregate's composition with Portland cements and a new endodontic cement. *J Endod* 2009; **35**: 243–250.
18. Asgary S, Parirokh M, Eghbal MJ, Brink F. A comparative study of white mineral trioxide aggregate and white Portland cements using X-ray microanalysis. *Aust Endod J* 2004; **30**: 89–92.
19. Oliveira MG de, Xavier CB, Demarco FF, Pinheiro ALB, Costa AT, Pozza DH. Comparative chemical study of MTA and Portland cements. *Braz Dent J* 2007; **18**: 3–7.
20. Hwang Y-C, Lee S-H, Hwang I-N, Kang I-C, Kim M-S, Kim S-H *et al.* Chemical composition, radiopacity, and biocompatibility of Portland cement with bismuth oxide. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2009; **107**: e96–e102.
21. Dammaschke T, Gerth HUV, Züchner H, Schäfer E. Chemical and physical surface and bulk material characterization of white ProRoot MTA and two Portland cements. *Dent Mater* 2005; **21**: 731–738.
22. Mindness S, Young J. *Concrete*. Englewood, NJ, USA: Prentice-Hall, 1981.
23. Camilleri J. Hydration mechanisms of mineral trioxide aggregate. *Int Endod J* 2007; **40**: 462–470.
24. Birchall JD, Howard AJ, Bailey JE. On the hydration of Portland Cement. *Proc Roy Soc A: Math Phys Eng Sci* 1978; **360**: 445–453.
25. Sarkar NK, Caicedo R, Ritwik P, Moiseyeva R, Kawashima I. Physicochemical basis of the biologic properties of mineral trioxide aggregate. *J Endod* 2005; **31**: 97–100.
26. Kogan P, He J, Glickman GN, Watanabe I. The effects of various additives on setting properties of MTA. *J Endod* 2006; **32**: 569–572.
27. Lee ES. A new mineral trioxide aggregate root-end filling technique. *J Endod* 2000; **26**: 764–765.
28. Torabinejad M, Hong CU, McDonald F, Pitt Ford TR. Physical and chemical properties of a new root-end filling material. *J Endod* 1995; **21**: 349–353.
29. Aquilina JW. *The physical properties of accelerated Portland cement*. MSc,1999. Project Report, University of London.
30. Duarte MAH, Demarchi ACC de O, Yamashita JC, Kuga MC, Fraga S de C. pH and calcium ion release of 2 root-end filling materials. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2003; **95**: 345–347.
31. Antunes Bortoluzzi E, Juárez Broon N, Antonio Hungaro Duarte M, De Oliveira Demarchi ACC, Monteiro Bramante C. The use of a setting accelerator and its effect on pH and calcium ion release of mineral trioxide aggregate and white Portland cement. *J Endod* 2006; **32**: 1194–1197.
32. AlAnezi AZ, Zhu Q, Wang Y-H, Safavi KE, Jiang J. Effect of selected accelerants on setting time and biocompatibility of mineral trioxide aggregate (MTA). *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2011; **111**: 122–127.
33. Wiltbank KB, Schwartz SA, Schindler WG. Effect of selected accelerants on the physical properties of mineral trioxide aggregate and Portland cement. *J Endod* 2007; **33**: 1235–1238.
34. Huang T-H, Shie M-Y, Kao C-T, Ding S-J.

The effect of setting accelerator on properties of mineral trioxide aggregate. *J Endod* 2008; **34**: 590–593.
35. Lee B-N, Hwang Y-C, Jang J-H, Chang H-S, Hwang I-N, Yang S-Y *et al*. Improvement of the properties of mineral trioxide aggregate by mixing with hydration accelerators. *J Endod* 2011; **37**: 1433–1436.
36. Saghiri MA, Asgar K, Lotfi M, Garcia-Godoy F. Nanomodification of mineral trioxide aggregate for enhanced physiochemical properties. *Int Endod J* 2012; **45**: 979–988.
37. Ber BS, Hatton JF, Stewart GP. Chemical modification of proroot mta to improve handling characteristics and decrease setting time. *J Endod* 2007; **33**: 1231–1234.
38. Hsieh S-C, Teng N-C, Lin Y-C, Lee P-Y, Ji D-Y, Chen C-C *et al*. A novel accelerator for improving the handling properties of dental filling materials. *J Endod* 2009; **35**: 1292–1295.
39. Coomaraswamy KS, Lumley PJ, Hofmann MP. Effect of bismuth oxide radioopacifier content on the material properties of an endodontic Portland cement-based (MTA-like) system. *J Endod* 2007; **33**: 295–298.
40. Kim E-C, Lee B-C, Chang H-S, Lee W, Hong C-U, Min K-S. Evaluation of the radiopacity and cytotoxicity of Portland cements containing bismuth oxide. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2008; **105**: e54–e57.
41. Min K-S, Chang H-S, Bae J-M, Park S-H, Hong C-U, Kim E-C. The induction of heme oxygenase-1 modulates bismuth oxide-induced cytotoxicity in human dental pulp cells. *J Endod* 2007; **33**: 1342–1346.
42. International Organization for Standardization. *Specification for Dental Root Canal Sealing Materials*. ISO 6876 Section 7.8: p14. British Standards Institution, 1986.
43. Hungaro Duarte MA, Minotti PG, Rodrigues CT, Zapata RO, Bramante CM, Tanomaru Filho M *et al*. Effect of different radiopacifying agents on the physicochemical properties of white Portland cement and white mineral trioxide aggregate. *J Endod* 2012; **38**: 394–397.
44. Orosco FA, Bramante CM, Garcia RB, Bernadineli N, Moraes IG de. Sealing ability of gray MTA Angelus™ , CPM™ and MBPc used as apical plugs. *J Appl Oral Sci* 2008; **16**: 50–54.
45. Gomes-Filho JE, Watanabe S, Bernabé PFE, De Moraes Costa MT. A mineral trioxide aggregate sealer stimulated mineralization. *J Endod* 2009; **35**: 256–260.
46. Zhang W, Li Z, Peng B. Assessment of a new root canal sealer's apical sealing ability. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2009; **107**: e79–e82.
47. Shokouhinejad N, Nekoofar MH, Razmi H, Sajadi S, Davies TE, Saghiri MA *et al*. Bioactivity of EndoSequence root repair material and bioaggregate. *Int Endod J* 2012; **45**: 1127–1134.
48. Asgary S, Shahabi S, Jafarzadeh T, Amini S, Kheirieh S. The properties of a new endodontic material. *J Endod* 2008; **34**: 990–993.
49. Asgary S, Eghbal MJ, Parirokh M. Sealing ability of a novel endodontic cement as a root-end filling material. *J Biomed Mater Res A* 2008; **87**: 706–709.
50. Asgary S, Eghbal MJ, Parirokh M, Ghoddusi J. Effect of two storage solutions on surface topography of two root-end fillings. *Aust Endod J* 2009; **35**: 147–152.
51. Zhang H, Pappen FG, Haapasalo M. Dentin enhances the antibacterial effect of mineral trioxide aggregate and bioaggregate. *J Endod* 2009; **35**: 221–224.
52. DiaRoot® Bioaggregate Material Safety Data Sheet [Internet]. 2007 [cited 2011 Nov 27]. Available from: **http://www.diadent.com/MSDS/DiaRoot%20MSDS.pdf**
53. Grech L, Mallia B, Camilleri J. Characterization of set Intermediate Restorative Material, Biodentine, Bioaggregate and a prototype calcium silicate cement for use as root-end filling materials. *Int Endod J* 2013; **46**: 632–641. doi: 10.1111/iej.12039. Epub 2013 Jan4.
54. Park J-W, Hong S-H, Kim J-H, Lee S-J, Shin S-J. X-Ray diffraction analysis of white ProRoot MTA and Diadent BioAggregate. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2010; **109**: 155–158.
55. Grech L, Mallia B, Camilleri J. Investigation of the physical properties of tricalcium silicate cement-based root-end filling materials. *Dent Mater* 2013; **29**: e20–e28.
56. Scientific File on Biodentine. R & D Department, Septodont, Saint Maur des Fosśes, France.
57. Han L, Okiji T. Uptake of calcium and silicon released from calcium silicate-based endodontic materials into root canal dentine. *Int Endod J* 2011; **44**: 1081–1087.
58. Atmeh AR, Chong EZ, Richard G, Festy F, Watson TF. Dentin-cement interfacial interaction: calcium silicates and polyalkenoates. *J Dent Res* 2012; **91**: 454–459.
59. Tech Biosealer Material Safety Data Sheet [Internet]. 2010 [cited 2012 Feb 29]. Available from: **http://www.isasan.com/Libraries/Product_Doc/MSDS_ENG.sflb.ashx**
60. Tech Biosealer Brochure [Internet] [cited 2012 Feb 29]. Available from: **http://www.isasan.com/Libraries/Product_Doc/BIOSEALER_ENGLISH.sflb.ashx**
61. Gombia M, Bortolotti V, De Carlo B, Mongiorgi R, Zanna S, Fantazzini P. Nanopore structure buildup during endodontic cement hydration studied by time-domain nuclear magnetic resonance of lower and higher mobility 1H. *J Phys Chem B* 2010; **114**: 1767–1774.
62. Gandolfi M, Bortolotti V, Carlos B, Mongiorgi R, Zanna S, Fantazzini P. Biocompatibility and sealing of Tech Biosealer Endo as function of bioactivity. *J Dent Res* 2010; **89B**: 138404.
63. Hakki S, Bozkurt B, Ozcopur B, Gandolfi M, Prati C, Belli S. Real-time analysis of cytotoxicity of current root-canal sealers on cementoblasts. *J Dent Res* 2011; **90A**: 144001.
64. Prati C, Siboni F, Chersoni S, Taddei P, Gandolfi M. Lack of bioactivity of commercial endodontic sealers. *J Dent Res* **90A**: 149988.
65. DFUs-MTAPLUS-6-30-12EN.pdf [Internet] [cited 2013 Apr 16]. Available from: **http://avalonbiomed.com/wp-content/uploads/2012/07/DFUs-MTAPLUS-6-30-12EN.pdf**
66. Formosa LM, Mallia B, Camilleri J. Mineral trioxide aggregate with anti-washout gel – Properties and microstructure. *Dent Mater* 2013; **29**: 294–306.
67. Formosa LM, Mallia B, Camilleri J. A quantitative method for determining the antiwashout characteristics of cement-based dental materials including mineral

trioxide aggregate. *Int Endod J* 2013; **46**: 179–186.
68. Leiendecker AP, Qi Y-P, Sawyer AN, Niu L-N, Agee KA, Loushine RJ *et al*. Effects of calcium silicate-based materials on collagen matrix integrity of mineralized dentin. *J Endod* 2012; **38**: 829–833.
69. Shen Q, Sun J, Wu J, Liu C, Chen F. An *in vitro* investigation of the mechanical-chemical and biological properties of calcium phosphate/calcium silicate/bismutite cement for dental pulp capping. *J Biomed Mater Res Part B Appl Biomater* 2010; **94**: 141–148.
70. Gandolfi MG, Ciapetti G, Taddei P, Perut F, Tinti A, Cardoso MV *et al*. Apatite formation on bioactive calcium-silicate cements for dentistry affects surface topography and human marrow stromal cells proliferation. *Dent Mater* 2010; **26**: 974–992.
71. Kim M, Ko H, Yang W, Lee Y, Kim S, Mante FK. A new resin-bonded retrograde filling material. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2009; **108**: e111–e116.
72. Gomes-Filho JE, De Faria MD, Bernabé PFE, Nery MJ, Otoboni-Filho JA, Dezan-Júnior E *et al*. Mineral trioxide aggregate but not light-cure mineral trioxide aggregate stimulated mineralization. *J Endod* 2008; **34**: 62–65.
73. Gandolfi MG, Taddei P, Siboni F, Modena E, Ciapetti G, Prati C. Development of the foremost light-curable calcium-silicate MTA cement as root-end in oral surgery. Chemical-physical properties, bioactivity and biological behavior. *Dent Mater* 2011; **27**: e134–e157.
74. TheraCal Material Safety Data Sheet [Internet] 2011 [cited 2012 Feb 29]. Available from: **http://www.bisco.com/instructions/TheraCal%20LC%20MSDS.pdf**
75. Hebling J, Lessa FCR, Nogueira I, Carvalho RM, Costa CAS. Cytotoxicity of resin-based light-cured liners. *Am J Dent* 2009; **22**: 137–142.
76. Gandolfi MG, Siboni F, Prati C. Chemical-physical properties of TheraCal, a novel light-curable MTA-like material for pulp capping. *Int Endod J* 2012; **45**: 571–579.
77. Chung H, Kim M, Ko H, Yang W. Evaluation of physical and biologic properties of the mixture of mineral trioxide aggregate and 4-META/MMA-TBB resin. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2011; **112**: e6–e11.
78. Gandolfi MG, Taddei P, Siboni F, Modena E, De Stefano ED, Prati C. Biomimetic remineralization of human dentin using promising innovative calcium-silicate hybrid "smart" materials. *Dent Mater* 2011; **27**: 1055–1069.
79. Formosa LM, Mallia B, Camilleri J. The chemical properties of light- and chemical-curing composites with mineral trioxide aggregate filler. *Dent Mater* 2013; **29**: e11–e19.